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Measuring Black Hole Masses Using Ionized Gas Kinematics

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Abstract. We describe techniques for measuring the central masses of galaxies using emission-line kinematics observed with the *Hubble Space Telescope*. For accurate results, it is necessary to model various instrumental effects, particularly the blurring due to the telescope PSF and the width of the spectroscopic aperture. Observations of nuclear gas disks often reveal substantial internal velocity dispersions in the gas, suggesting that the disks may be partially pressure-supported. We also describe a technique for fitting 2-dimensional spectroscopic data directly in pixel space. This method may be useful for objects such as M84 that show highly complex and asymmetric line profiles.

1. Introduction

Supermassive black holes are thought to occur in the nuclei of all massive galaxies, or at least in those galaxies having a bulge component. Recent studies have shown that the black hole mass is correlated loosely with the host galaxy bulge luminosity (Kormendy & Richstone 1995; Magorrian et al. 1998) and correlated tightly with the stellar velocity dispersion of the bulge (Ferrarese & Merritt 2000; Gebhardt et al. 2000). However, the slope of the $M_{\text{BH}} - \sigma$ relation, and the amount of intrinsic scatter in the correlation, remain somewhat controversial. For further progress, more black hole masses must be measured, and with the highest accuracy possible.

Disks of ionized gas and dust with radii of tens to hundreds of parsecs are found in the nuclei of $\sim 10 - 20\%$ of nearby galaxies. With *HST* spectra, it is possible to map out the velocity structure of these disks and determine the central masses. In principle, the measurement is straightforward: the goal is simply to measure the rotation speed of a circular disk. However, the region with the greatest diagnostic power for determining the central mass is generally at or near the resolution limit of *HST*. Near the nucleus, there are steep gradients in rotation velocity and emission-line surface brightness across the spectroscopic aperture. In addition, the gas often has a substantial internal velocity dispersion, which may affect the dynamical properties of the disks. All of these effects must be taken into account in order to derive accurate black hole masses from the data.

2. Measurement Techniques

Instrumental Effects. The velocity fields in circumnuclear disks can be measured with the STIS spectrograph on *HST*, usually with a slit width of $0''.1$ or $0''.2$. Due to the telescope PSF and the nonzero aperture size, the innermost Keplerian rotation curve is blurred into a smooth velocity gradient across the nucleus. Only for the largest black holes will the Keplerian portion of the velocity field be partly resolved. Kinematic analyses which do not take into account this instrumental blurring (e.g., Ferrarese et al. 1996) will tend to underestimate the true black hole masses, because an unblurred model will need a smaller central mass to reach a given rotation velocity near the nucleus.

We have developed modeling software that performs a complete simulation of the STIS observation, so that kinematic models for the rotating disk can be compared with the data in detail. The code calculates the propagation of full line profiles through the spectrograph slit, accounting for PSF blurring, aperture size, and the apparent wavelength shift of light that enters the slit off-center. These techniques have been applied to measure the central mass of the S0 galaxy NGC 3245 (Barth et al. 2001).

Emission-line Surface Brightness. Observations of the velocity field are weighted by the surface brightness of emission lines, which sometimes show a sharp, nearly unresolved “spike” at the nucleus. The measured velocities near the nucleus can be very sensitive to the brightness profile of this central spike. In addition, a nonuniform distribution of emission-line surface brightness can distort the shape of the radial velocity curves if a patch of emission is located off-center in the slit (Figure 1).

Disk Orientation Parameters. At least 3 slit positions are needed to fully constrain the orientation of the disk. For NGC 3245, we used 5 parallel positions covering the inner arcsecond. The off-nuclear slit positions give enough kinematic information to tightly constrain the disk inclination and the major axis position angle, eliminating what would otherwise be a significant source of uncertainty in the analysis.

Intrinsic Velocity Dispersion and Asymmetric Drift. Our modeling code includes all of the major sources of line broadening that contribute to the observed linewidths. These include the point-source line-spread function, the broadening due to the nonzero width of the slit, the diffusion of charge on the CCD, and the rotational broadening for the portion of the disk subtended by the slit aperture. The models for NGC 3245 demonstrate that the disk cannot be dynamically cold: the gas has an intrinsic velocity dispersion which rises to $\sim 150 \text{ km s}^{-1}$ at the nucleus.

Substantial internal velocity dispersions are observed in most circumnuclear disks of this type. This suggests that the disks may be partially pressure-supported, and that the black hole mass inferred from pure circular rotation models may be an underestimate. For NGC 3245, we apply a correction for this effect using the asymmetric drift equation of stellar dynamics; in this case the effect on the black hole mass is only 12%, but it may be larger for other galaxies with more turbulent disks.

For NGC 3245, we find $M_{\text{BH}} = (2.1 \pm 0.5) \times 10^8 M_{\odot}$. The error budget includes uncertainties due to the kinematic model fitting, the measurement of

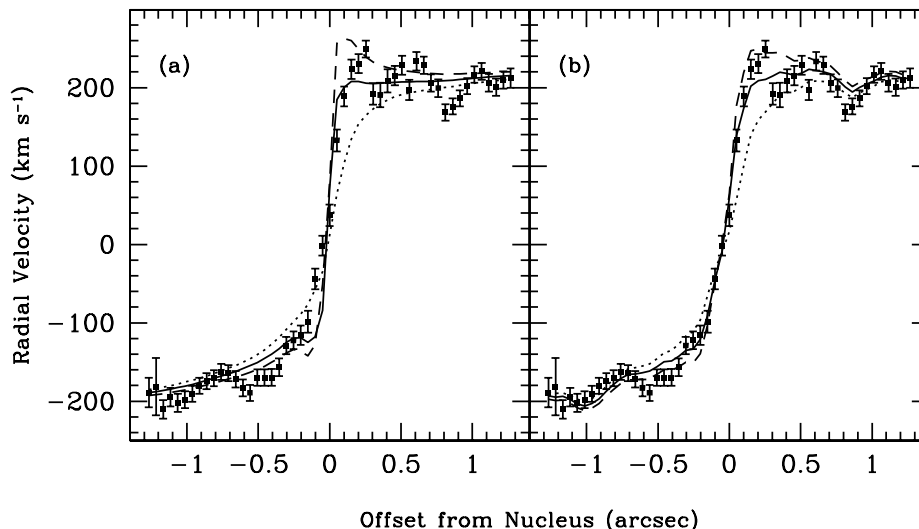


Figure 1. Central velocity curve for NGC 3245 measured from STIS data, using the $0''.2$ -wide slit. The model curves are calculated for $M_{\text{BH}} = 0, 2 \times 10^8$, and $4 \times 10^8 M_{\odot}$ and a fixed value of the stellar mass-to-light ratio. (a) Model curves calculated assuming a smooth emission-line surface brightness distribution of the form $S = S_0 + S_1 e^{-r/r_0}$. (b) The *same* kinematic models, calculated using a WFPC2 $\text{H}\alpha + [\text{N II}]$ image as a more accurate map of the emission-line surface brightness. This figure demonstrates that many of the irregularities seen in the rotation curve are not the result of kinematic disturbances, but are simply due to the patchy distribution of emission-line light across the slit.

the stellar luminosity profile, the distance to the galaxy, and differences between the kinematics of $\text{H}\alpha$ and $[\text{N II}]$.

3. Direct Fitting of Emission-Line Profiles.

The analysis technique described above, based on fitting the measured velocity curves, only works well if the emission-line profiles are close to Gaussian. This is not always the case; for example, the galaxy M84 (NGC 4374) has extremely complex line profiles near the nucleus. Bower et al. (1998) found that the line profiles in M84 show two kinematic components, a fast Keplerian component and a slowly rotating one. They fitted Keplerian disk models to the fast component and derived a central mass of $(0.9 - 2.6) \times 10^9 M_{\odot}$. More recently, Maciejewski & Binney (2001) showed that the two kinematic components actually both arise from the disk itself, because the slit is wide enough to subtend different portions of the disk having a wide range of velocities. As a result, the position and velocity

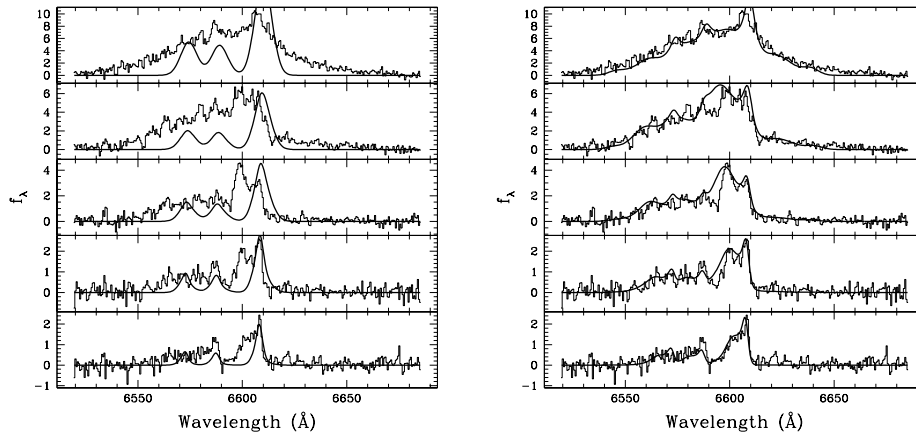


Figure 2. Preliminary model results for M84. Data and models are shown for the central row of the CCD spectrum (top panel) and for four off-nuclear rows. *Left panel:* A trial model assuming no black hole. Without a black hole, the emission profiles are nearly Gaussian and the model is unable to match the width and structure of the observed profiles. *Right panel:* A model calculated for $M_{\text{BH}} = 10^9 M_{\odot}$.

information become badly entangled in the central regions, and it is effectively impossible to measure a well-defined rotation curve for the inner disk.

To circumvent this problem, we have adapted our code to fit the emission profiles of the rotating disk *directly* in pixel space. This method makes use of all available information in the data, including the high-velocity wings of the line profiles. Preliminary results for M84 are shown in Figure 2. With $M_{\text{BH}} = 10^9 M_{\odot}$, the model naturally accounts for much of the structure in the line profiles: narrow cores and broad wings at the nucleus, extreme asymmetries, and even double-peaked profiles at some locations. While the fits are by no means perfect, these preliminary results demonstrate that direct profile fitting is a promising technique for extracting black hole masses from data showing highly asymmetric emission lines.

References

- Barth, A. J., Sarzi, M., Rix, H.-W., Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 2001, ApJ, in press (astro-ph/0012213)
- Bower, G., et al. 1998, ApJ, 492, L111
- Ferrarese, L., Ford, H. C., & Jaffe, W. 1996, ApJ, 470, 444
- Ferrarese, L., & Merritt, D. 2000, ApJ, 539, L9
- Gebhardt, K., et al. 2000, ApJ, 539, L13
- Kormendy, J., & Richstone, D. 1995, ARA&A, 33, 581
- Maciejewski, W., & Binney, J. 2001, MNRAS, 323, 831
- Magorrian, J., et al. 1998, AJ, 115, 2285